Optical and Infrared Imaging Studies of Debris Disks

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New *Spitzer* results shown are in collaboration with The "Fab 4" GTO consortium (Mike Werner, PI)

Beyond Spitzer Workshop June 9 2004

What is Learned from High Resolution Debris Disk Imaging?

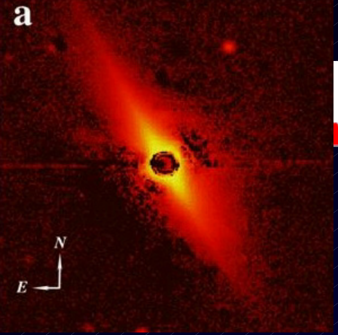
- **Confirms basic disk morphology of dust distribution**
  - *position angle*
  - *major and minor axes (outer radius of disk)*
- **Measurable disk parameters**
  - *Vertical profile (if close to edge-on)*
  - *Sharp radial edges (central holes, gaps, rings)*
  - *Non-axisymmetries from resonant trapping of dust*

Structures suggestive of planetary perturbations

- **Derivable disk parameters**
  - *Inclination*
  - *Radial surface brightness -> radial surface density profile*
  - *Vertical disk structure if close to edge-on (scale height, flaring)*
  - *Disk mass (if opacity known)*
  - *Dust properties: opacity $\kappa(\lambda)$, phase function*
- **Some of the derivable properties are degenerate**

Tools of the Trade

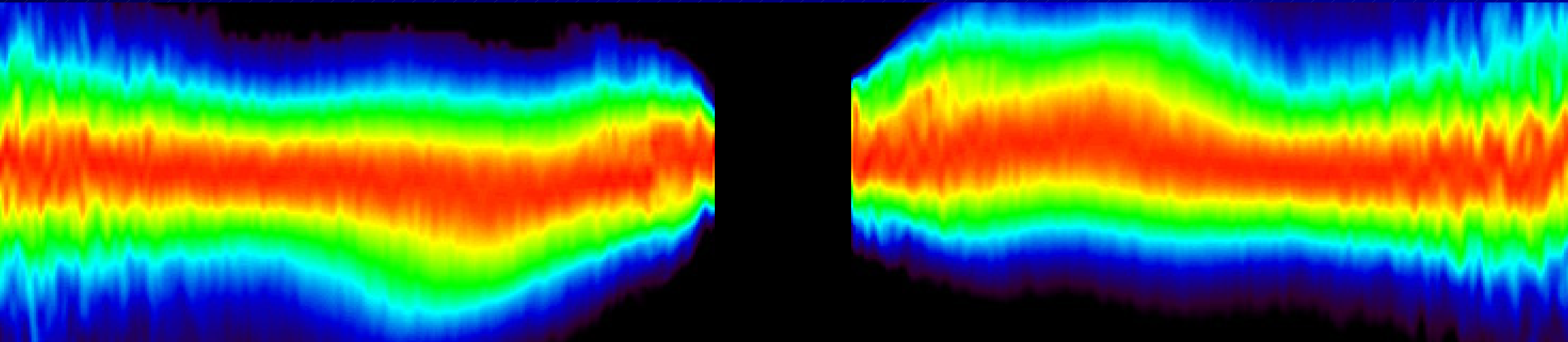
- **Groundbased optical / Near IR Adaptive Optics**
  - *Detects scattered light reflected from disk surface*
  - *Strehl ratio often a challenge with distant reference star*
  - *Unstable PSF wings make it difficult to observe extended dust within r < few arcsec. Only the 2 brightest, extended disks have been reliably detected.*
- **HST optical & near IR**
  - *Very stable PSF; can subtract modeled or empirical PSF to gain large factor in wings of PSF for WFPC2*
  - *ACS, STIS, and NICMOS coronagraphs; gain another factor of a few in contrast*
  - *Problems: coronagraphs have central exclusion zones (up to > 1 arcsec); no filter on STIS imaging; complex NICMOS PSF; hard to get time!*
- **Mid-IR Imaging**
  - *4 – 20 μm; detects disk thermal radiation*
  - *Mostly 10 m class telescopes due to high backgrounds*
  - *Best resolution ~0.3 arcsec*
- **Spitzer – finally up and returning disk images !**



Beta Pictoris: First Resolved Debris Disk

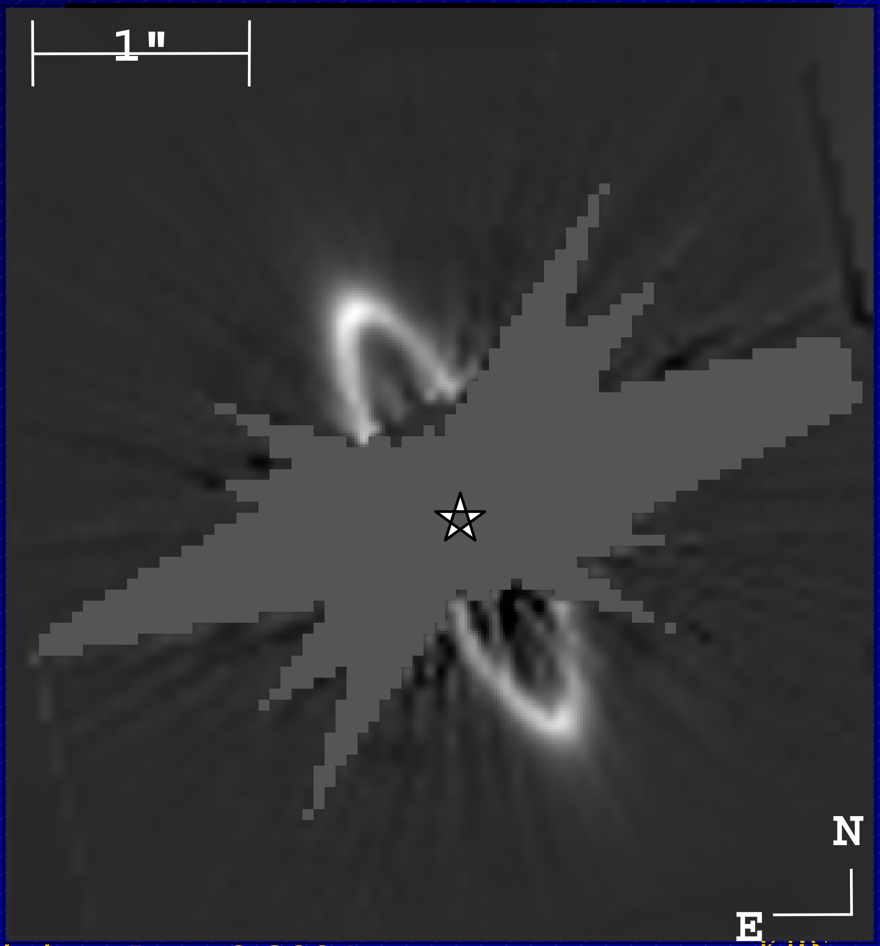
- **Optical & IR imaging observations:**
  - *Smith & Terrile (1984) ground based coronagraphic discovery*
  - *Kalas & Jewitt (1995) cataloged asymmetries*
  - *Burrows et al. (1995) first HST image discovered inner disk warp*
  - *Heap et al. 2001: STIS imaging; inner warp*
  - *Weinberger et al 2003: MIR imaging and spectroscopy; warps within 40 AU of star*
  - *Wahhaj et al. 2003: Keck MIR imaging; deconvolution of image suggests rings ?*

Below: Heap et al. 2001: HST/STIS image of inner warp



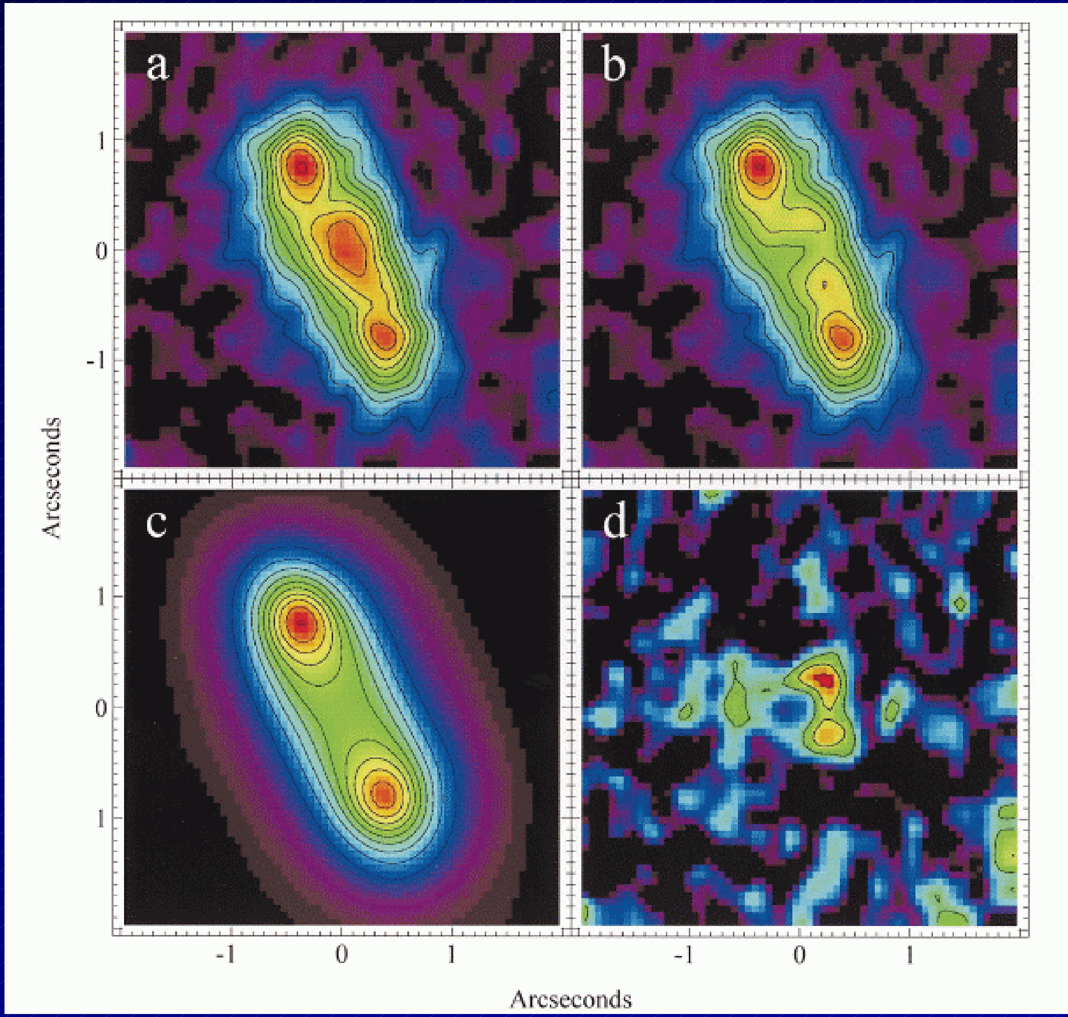
HR 4796A HST Imaging

- **Ae star in binary; 67 pc in TW Hya association**
- **Discovered by MIR imaging (Koerner et al. 1998; Jayawardhana et al. 1998)**
- **NICMOS imaging: Schneider et al. 1999**
  - *Ring that peaks at 70 AU; less than 17 AU in width; abrupt edges*
  - *Ring is redder than star; amount of scattered light accounts for IR excess seen by IRAS*
- **STIS image shown at left: asymmetric ansae (Schneider et al., in prep.)**

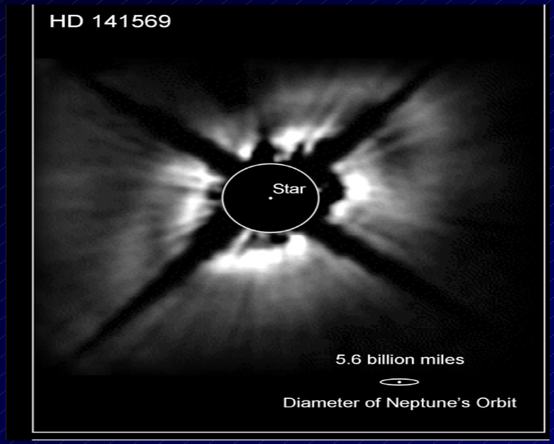


HR 4796A: Mid-IR Imaging

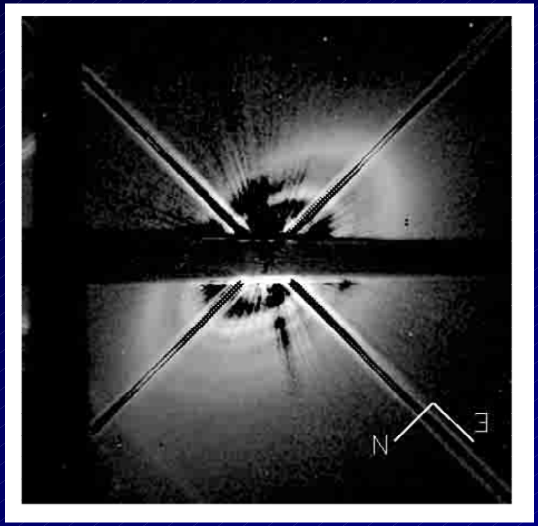
- Telesco et al. 2000
  - a) 18.2 μm image
  - b) PSF subtracted
  - c) Model
  - d) Residual after subtracting model
- All wavelengths show slight brightness asymmetry. Eccentric ring ?



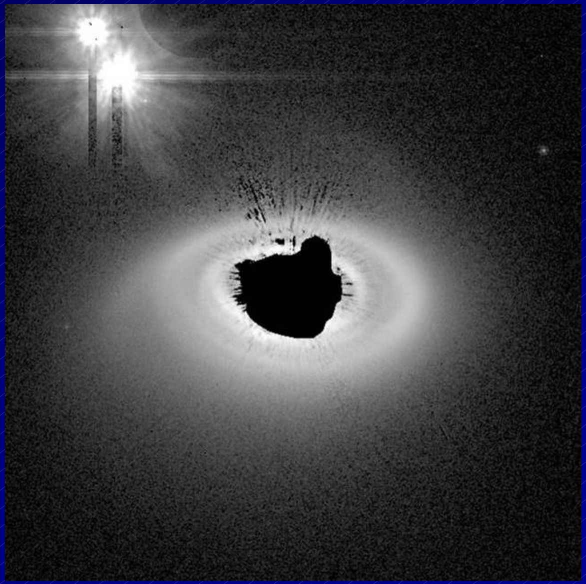
HST Images of HD 141569



NICMOS (Weinberger et al. 1999)



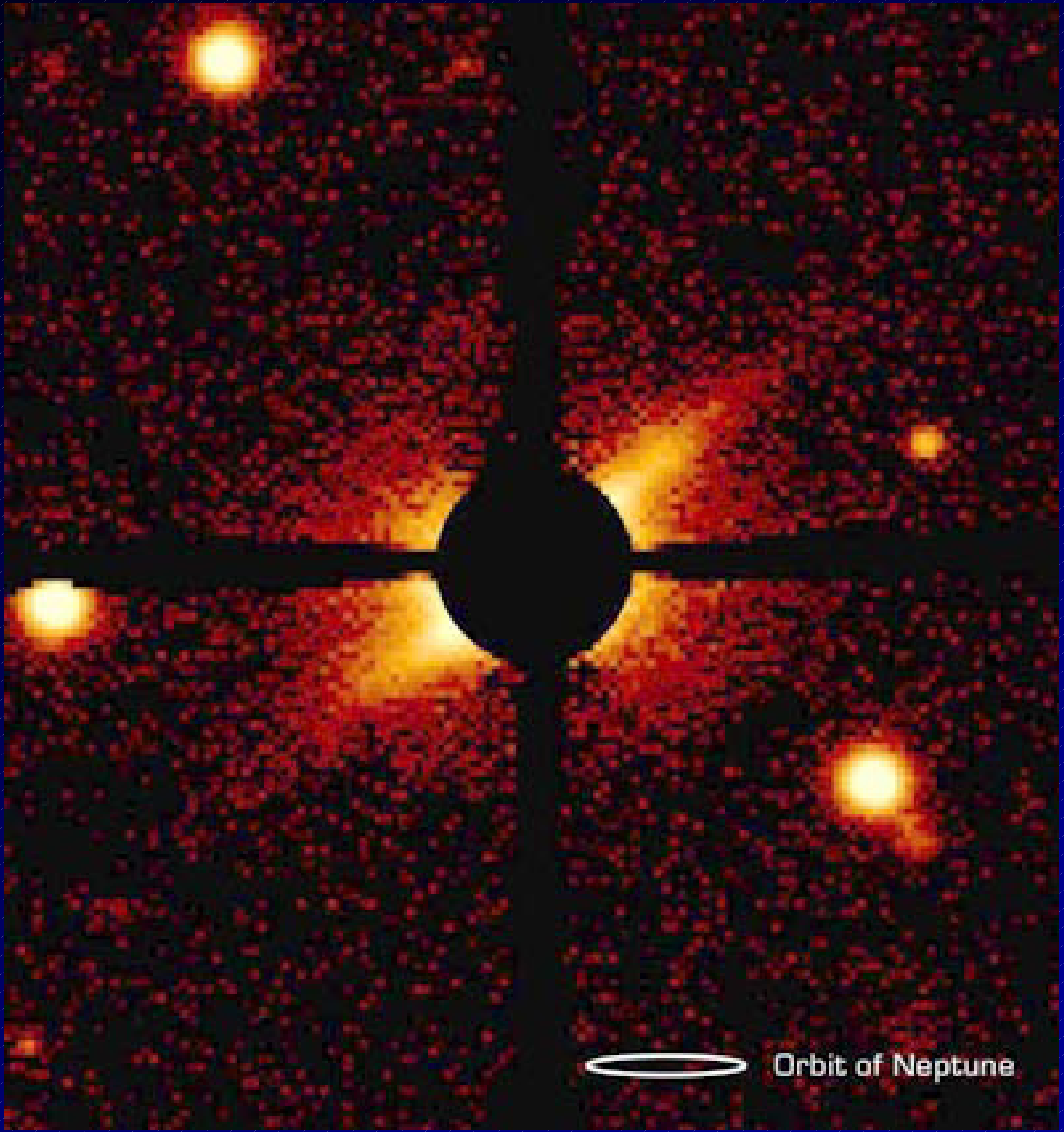
STIS (Mouillet et al. 2001)



ACS (Clampin et al. 2003)

Radial gap appears to be filled in;
Tail/arm may arise in tidal disturbances from nearby binary

Newly discovered debris disk of AU Mic (Liu, Kalas 2004)



First known debris disk with an M star primary

Nearest optically detectable debris disk to the Sun, d= 10 pc !

Star is in β Pic moving group, age 12 Myrs

There are few Spatially Resolved Debris Disks

Object	Scattered Light	Thermal Infrared	Millimeter Continuum	Millimeter Lines
ε Eridani	no	yes	yes	no
Fomalhaut	no	YES	yes	no
Vega	no	YES	yes	no
AU Mic	YES	TBD	no	TBD
β Pictoris	YES	YES	yes	no
HR 4796	YES	YES	no	no
HD 141569	YES	yes	no	no

How to identify resolvable disks in the mid-IR:

- **One can show that the characteristic angular scale for blackbody peak emission from a debris disk at wavelength λ can be approximated as**

  $$\theta = (\lambda^2 / d\, w^2)\ (L_\odot (1 - a) / 4\pi\sigma\varepsilon)^{1/2}$$

  where d is the source distance, w is the constant in Wien's law, a is the grain albedo, σ the Stefan-Boltzmann constant, and ε the grain emissivity at the wavelength in question
- **Calculate radii (in arcsec) for each star in the Hipparcos catalog. Compare these potential disk sizes with the resolution of mid/far-IR facilities. Results for 70 µm:**
  - *Spitzer (MIPS): perhaps a couple dozen stars with resolvable dust*
  - *Herschel (PACS): ~100 stars with resolvable dust*
  - *SAFIR: ~500 stars with resolvable dust. Aperture, longer λ make it better suited to resolving large number of disks than JWST*
  - *Whether the stars quoted above with resolvable 40 K emission regions actually have circumstellar dust is still to be determined*

Disk targets to spatially resolve with *Spitzer*

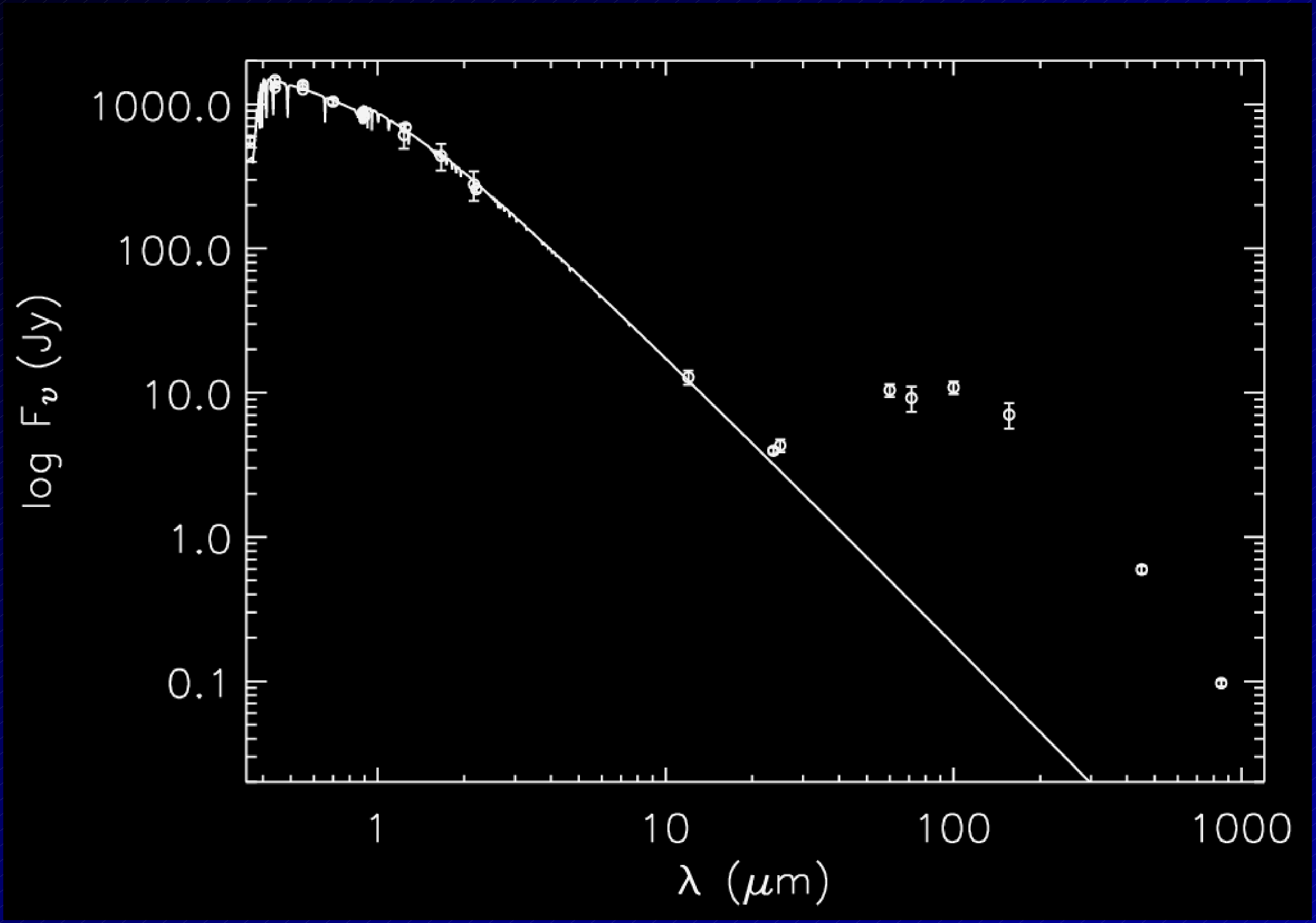
	IRAC 8 μm	MIPS 24 μm	MIPS 70 μm	MIPS 160 μm
FWHM (″)	2.0	6.0	16	39

- **Only nearby debris disks can be resolved**
- **Best targets are the "Fabulous four" debris disks resolved by IRAS and JCMT/SCUBA; all are resolved with *Spitzer***
  - *Fomalhaut : Early release observation, Stapelfeldt et al. (2004)*
  - *Beta Pictoris, epsilon Eridani, and Vega (observed April 2004)*
- **Other nearby debris disks ("The Dirty Dozen") are being surveyed at 70 μm:**
  - *<u>Unresolved with Spitzer:</u> alpha Coronae Borealis, beta Ursa Majoris, delta Vela, eta Tel, gamma Oph, and zeta Lep.*
  - *Still to be observed: beta Leo, tau Ceti, tau3 Eridani, gamma Trianguli, sigma Boo*

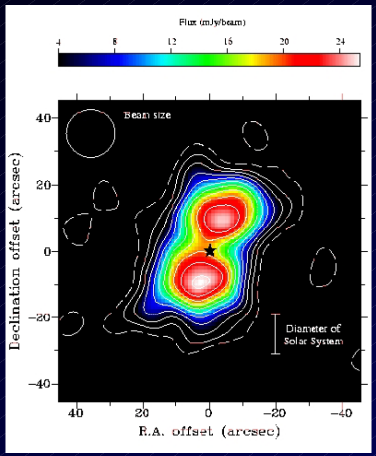
Spitzer Science Goals for Spatially Resolved Disks

- Use all three *Spitzer* instruments to resolve disk spatial structures that may indicate planetary perurbations on disks: central holes, clumps, asymmetries, radial gaps, warps, …
- Study the dust grain composition and search for a gas component using IRS and MIPS SED mode
- IRAC 4.5 µm search for substellar companions which may be perturbing the disks
- Provide a proving ground for disk models that will be broadly applied to other *Spitzer* disk survey datasets (GTO/Legacy/GO)

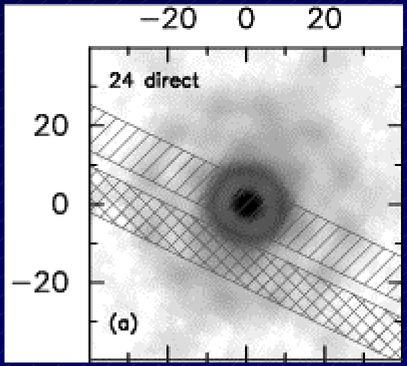
Fomalhaut spectral energy distribution

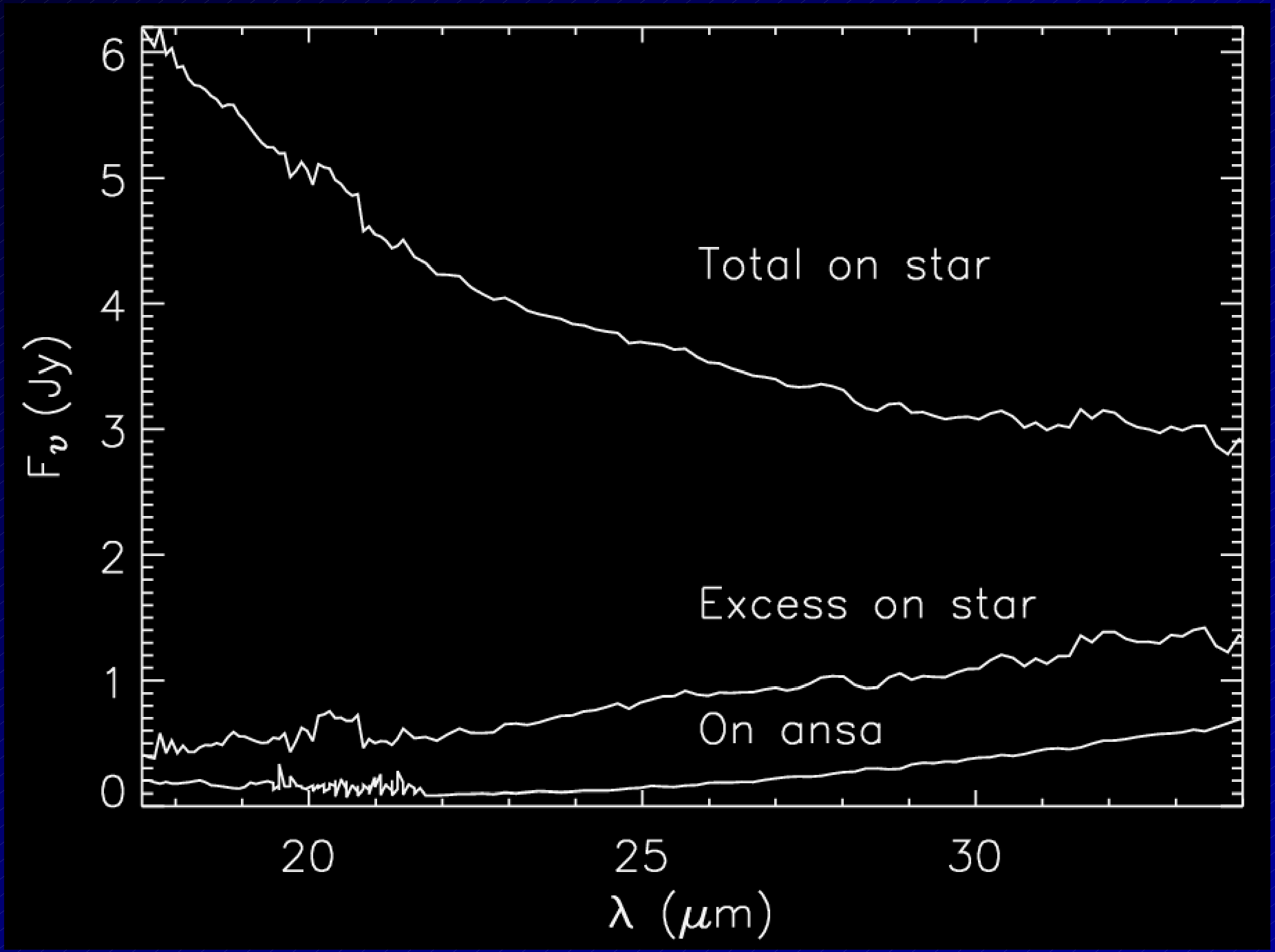


Fomalhaut long-lo spectrum

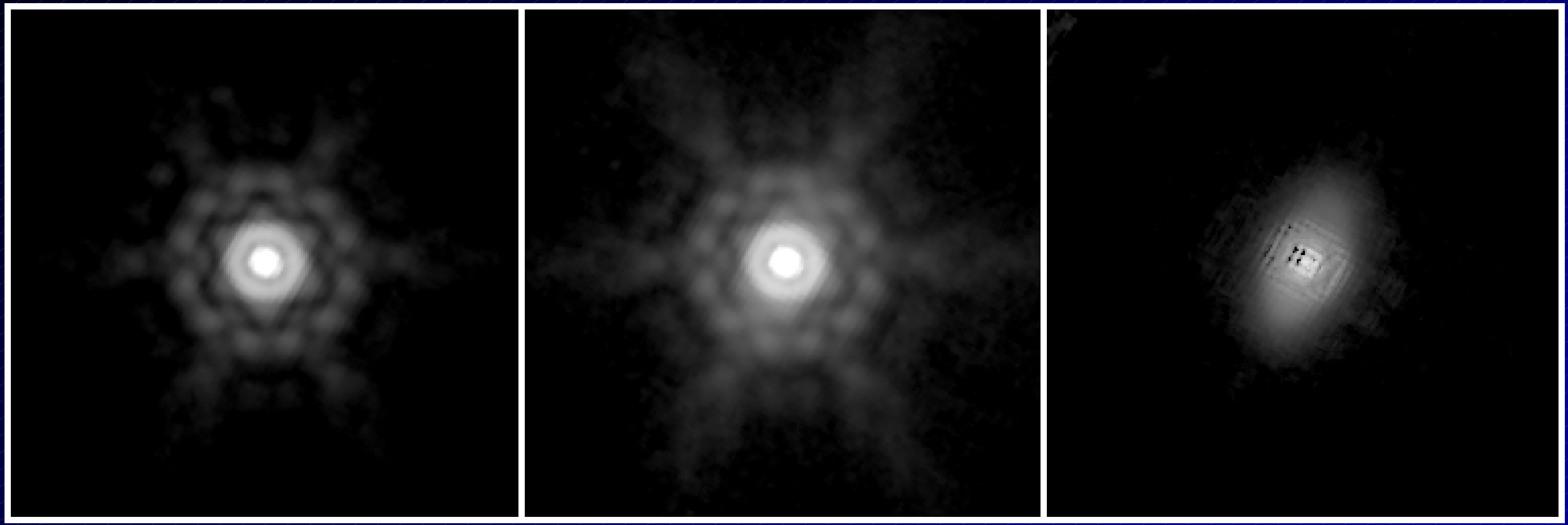


JCMT/SCUBA
850 μm
(Holland 1998)



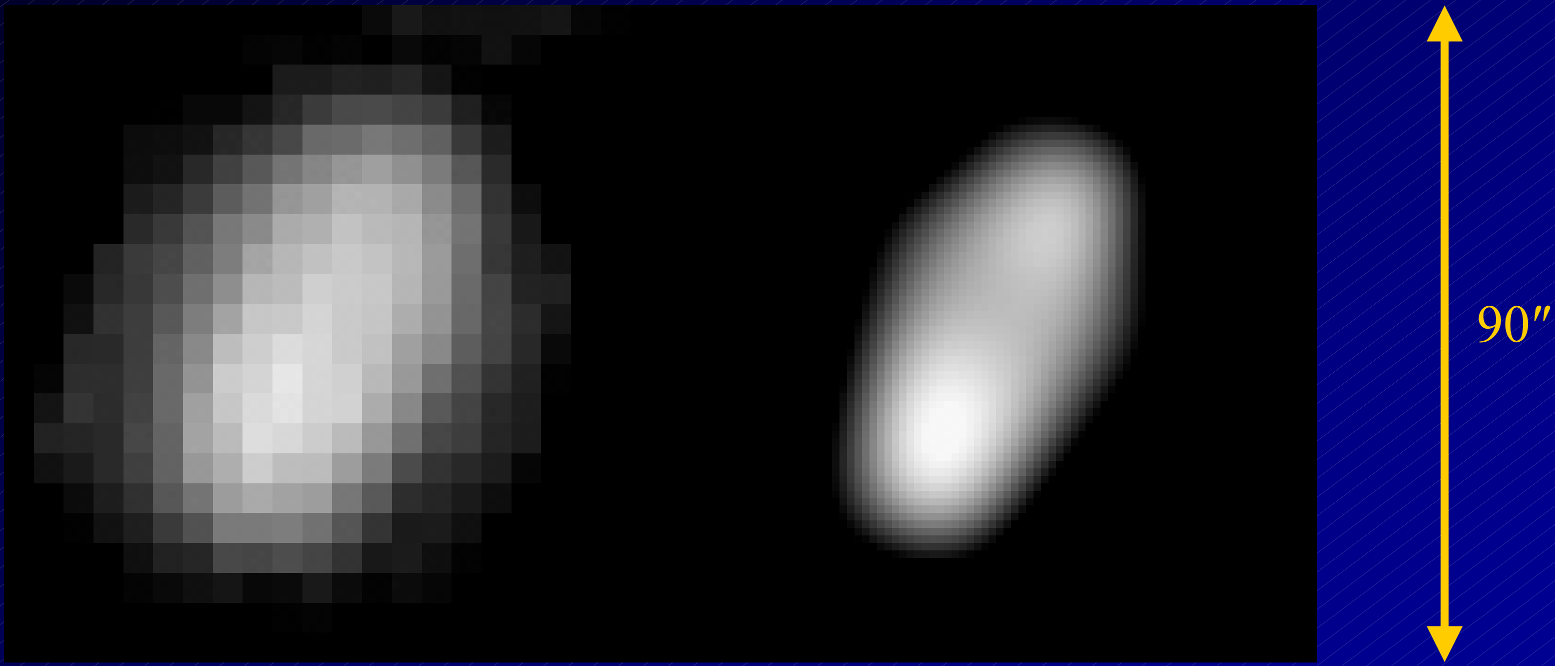


Fomalhaut MIPS 24 microns, 160" FOV



- **Left:** **Reference star image**
- **Center:** **Fomalhaut direct image**
- **Right:** **Dust disk revealed by PSF subtraction**
  - *Kurucz photosphere model fit determines scale factor*
  - *About 80% of 24 micron excess comes from unresolved core*

Fomalhaut MIPS 70 μm



Left: 70 micron fine scale image

Right: Deconvolution with 20 iterations of the HIRES algorithm

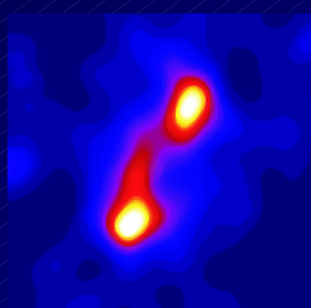
Aumann, Fowler & Melnick (1992)

see Velusamy's poster 41.33 today on its application to *Spitzer* data)

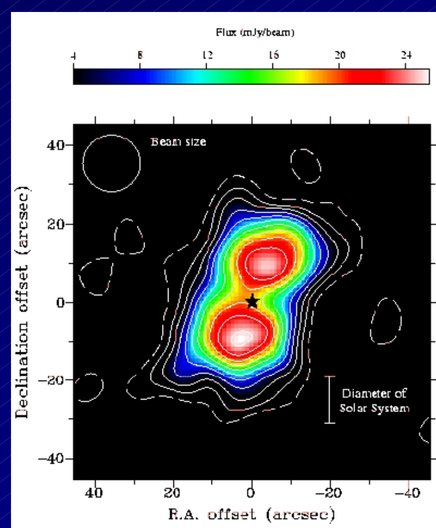
- Asymmetric bar of 70 μm emission overlying the submm ring

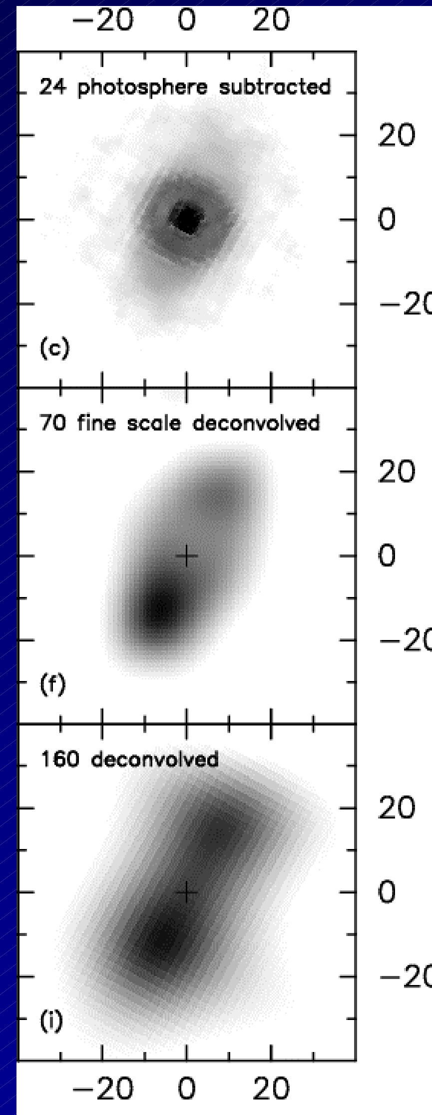
Putting Fomalhaut all together

JCMT/SCUBA
450 μm
(Holland 2003)



JCMT/SCUBA
850 μm
(Holland 1998)





MIPS
24 μm
(PSF-subtracted)

MIPS
70 μm

MIPS
160 μm

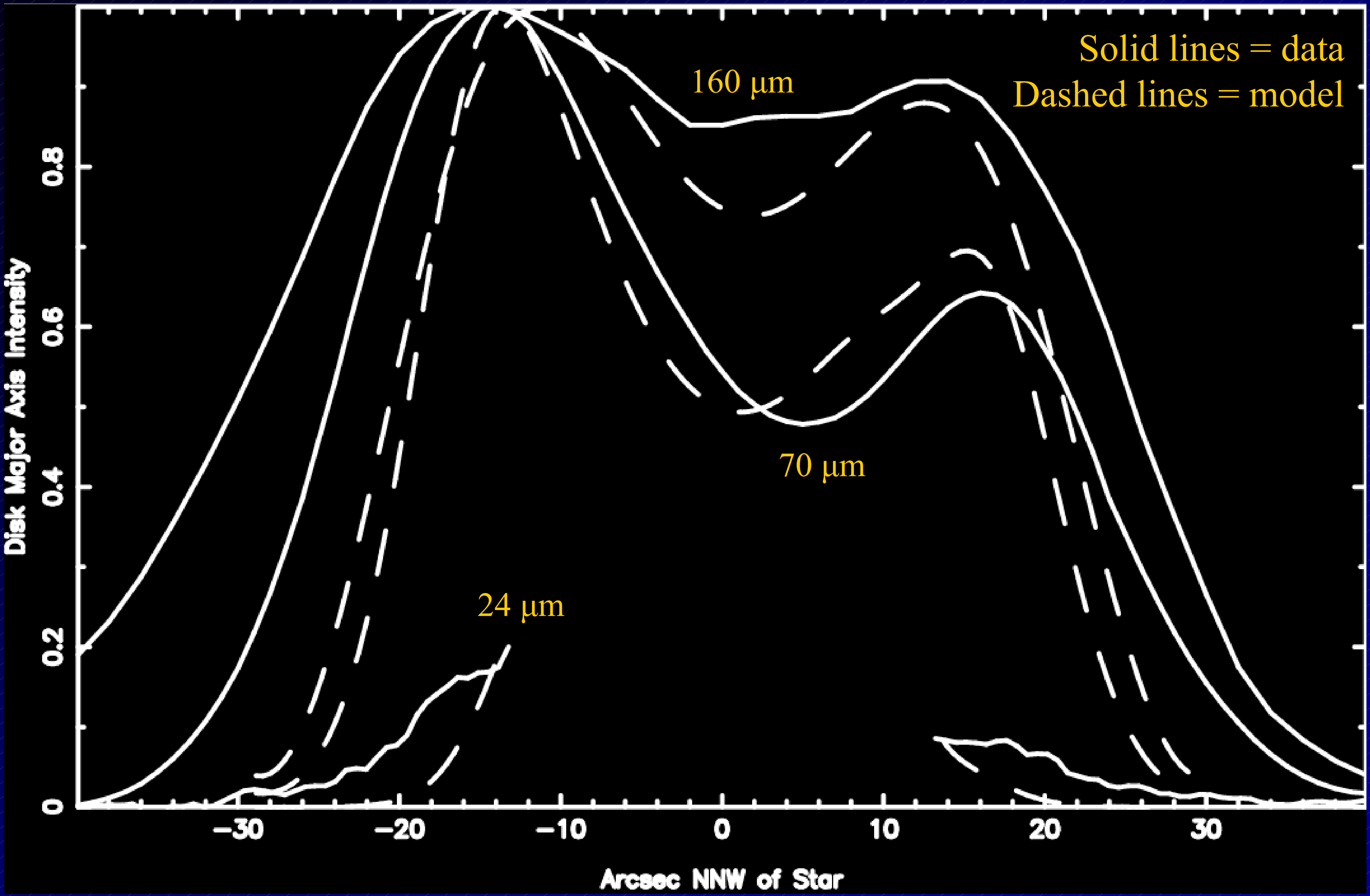
Fomalhaut Results Summary

- **No obvious spectral features detected with IRS**
- **Disk outer radius (20") is almost the same in all three MIPS bands, and in the submillimeter (Holland 2003)**
- **There is a warm disk component inside the submm ring:**
  - *Most of 24 μm excess is in compact central core, radius < 20 AU*
  - *Spectra show warmer, brighter excess on star than on disk ansa*
  - *To have gone undetected in the submm, this warm inner dust must have a low optical depth (< 10% of the outer dust ring)*
- **Asymmetric disk is detected in all three MIPS bands**
  - *SE ansa always brighter than NW ansa; difference greater at short wavelengths: 50%, 30%, 10% at 24, 70, and 160 μm respectively*
  - *JCMT maps suggested 10% asymmetry at 450 microns*
  - *Does asymmetry arise from planetary perturbations on the disk ?*

Explaining Fomalhaut's Disk Asymmetry

- **Recent parent body collision creating localized dust cloud ?**
  - *Pro: We know these collisions must be happening*
  - *Con: Particles should spread fairly rapidly; cloud not visible for long*
- **Dust particles trapped in mean-motion resonance with planet?**
  - *Pro: Could produce long-lived asymmetry*
  - *Con: May be hard to account for asymmetry variation with wavelength; trapped dust population won't have big radial extent*
- **Secular perturbations from planet in eccentric orbit on a continuous disk?**
  - *Disk particles will be forced onto eccentric orbits, tend toward apsidal alignment with planetary perturber.*
  - *Pro: Produces long-lived asymmetry, can account for its variation with wavelength*

Line cuts through Fomal-haut MIPS data & model



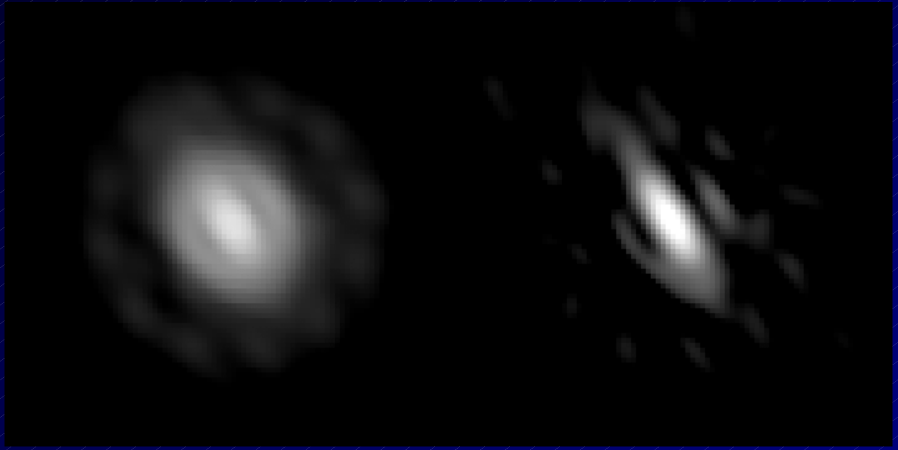
KRS

β Pictoris Results

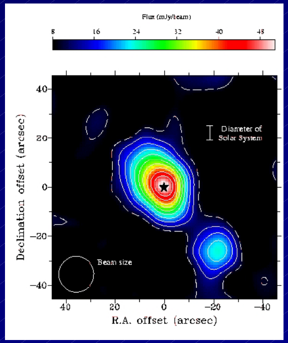
Spectral result: ISO H_2 detection
NOT confirmed at 17 μm

24 μm direct image

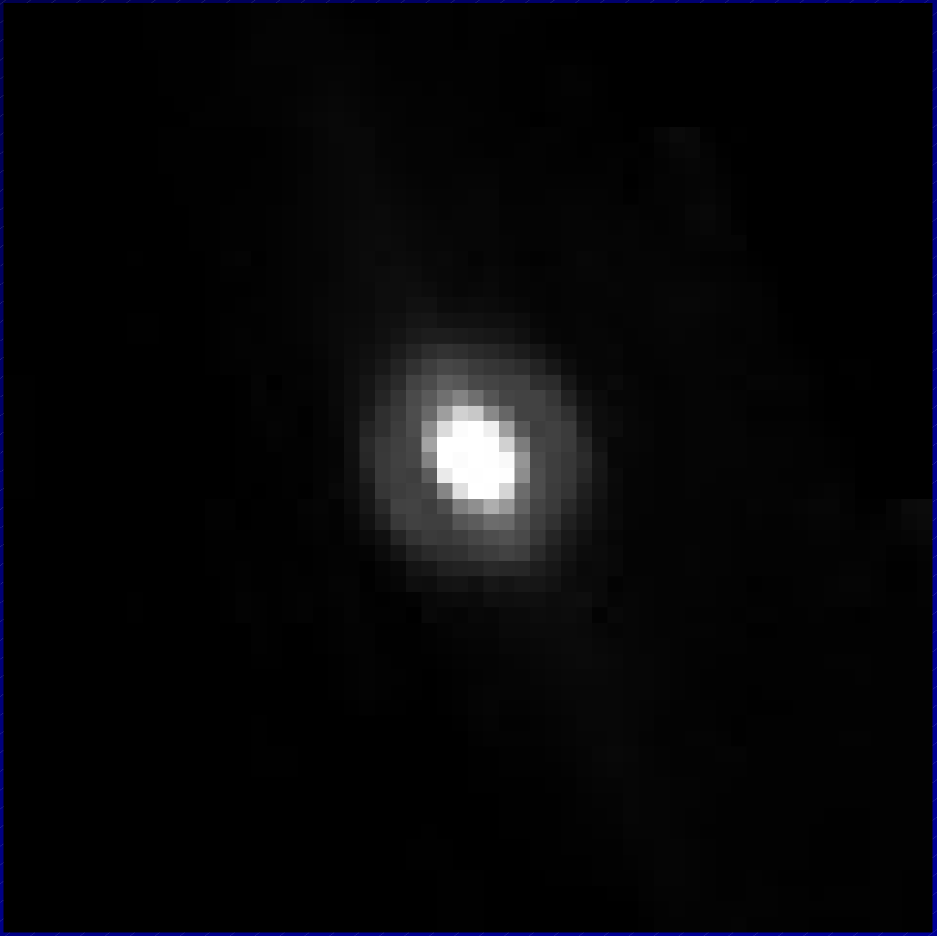
24 μm HIRES deconvolution



850 μm SCUBA image
(Holland et al. 1998)



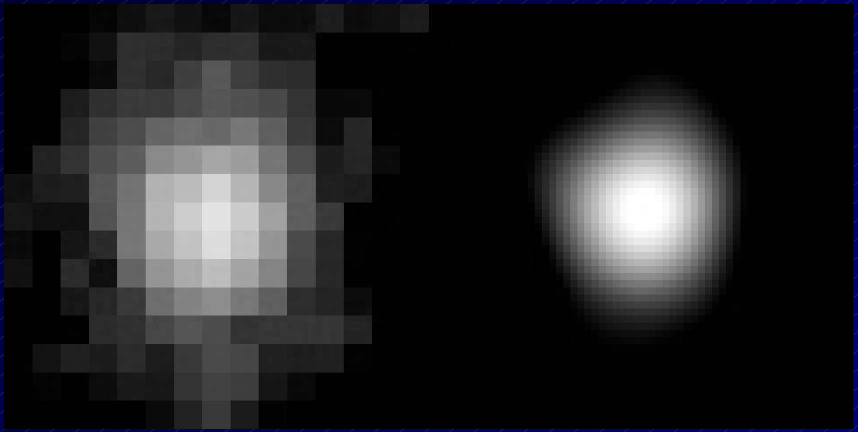
MIPS 70 μm default scale, 5′ FOV



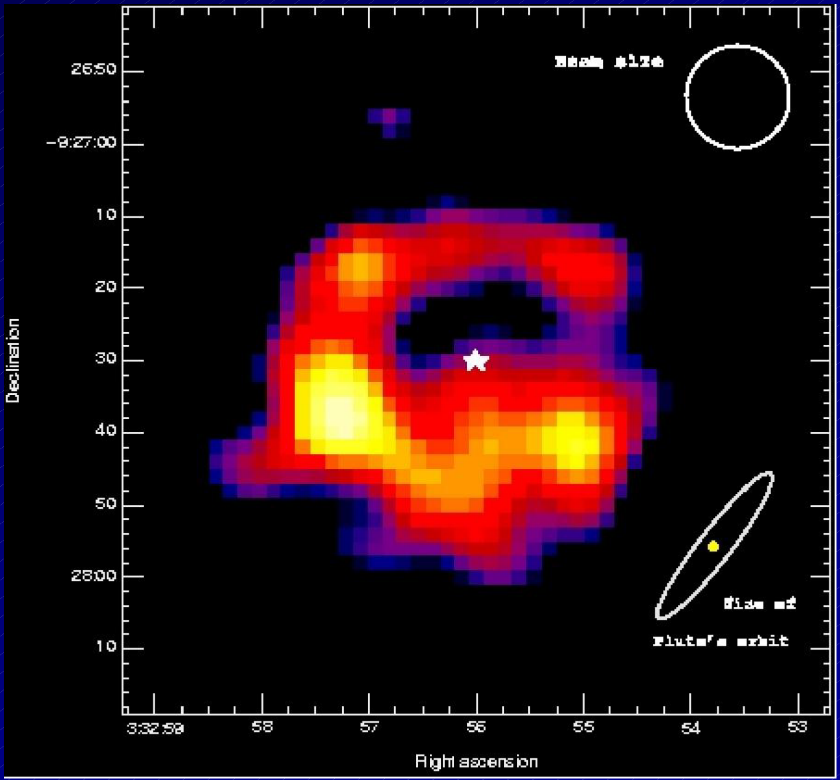
To appear in Van Cleve et al. 2005,
Chen et al. 2005

ε Eri MIPS 70 μm

Left: 70 μm fine scale
Right: HIRES deconvolution



SCUBA 850 μm (Greaves et al. 1998)



- No resolved excess at 24 μm
- 70 μm source has 15″ FWHM, and fills the interior of the submillimeter ring

To appear in Megeath et al. 2004

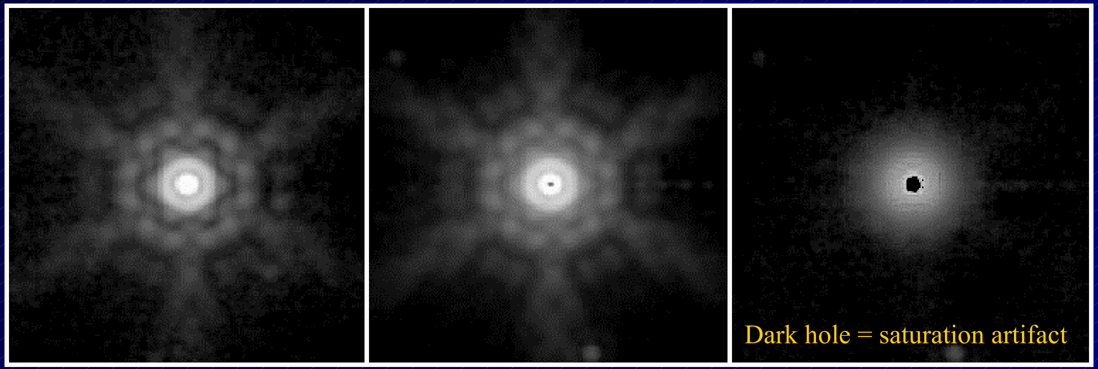
Vega observed with *Spitzer* / MIPS

(to appear in Su et al. 2004)

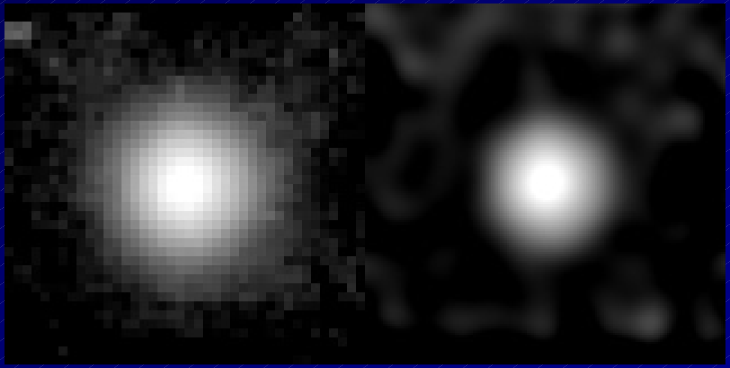
Spitzer images here are 160″ square

Reference star — Vega direct image — Vega PSF -subtracted

24 µm results: Emission extends to r> 40″

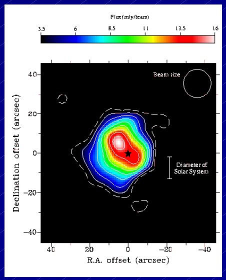


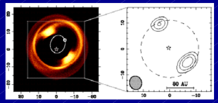
70 µm results: Source has ~25″ FWHM



Fine scale — HIRES deconvolution

Below left: SCUBA 850 µm map by Holland et al. (1998)



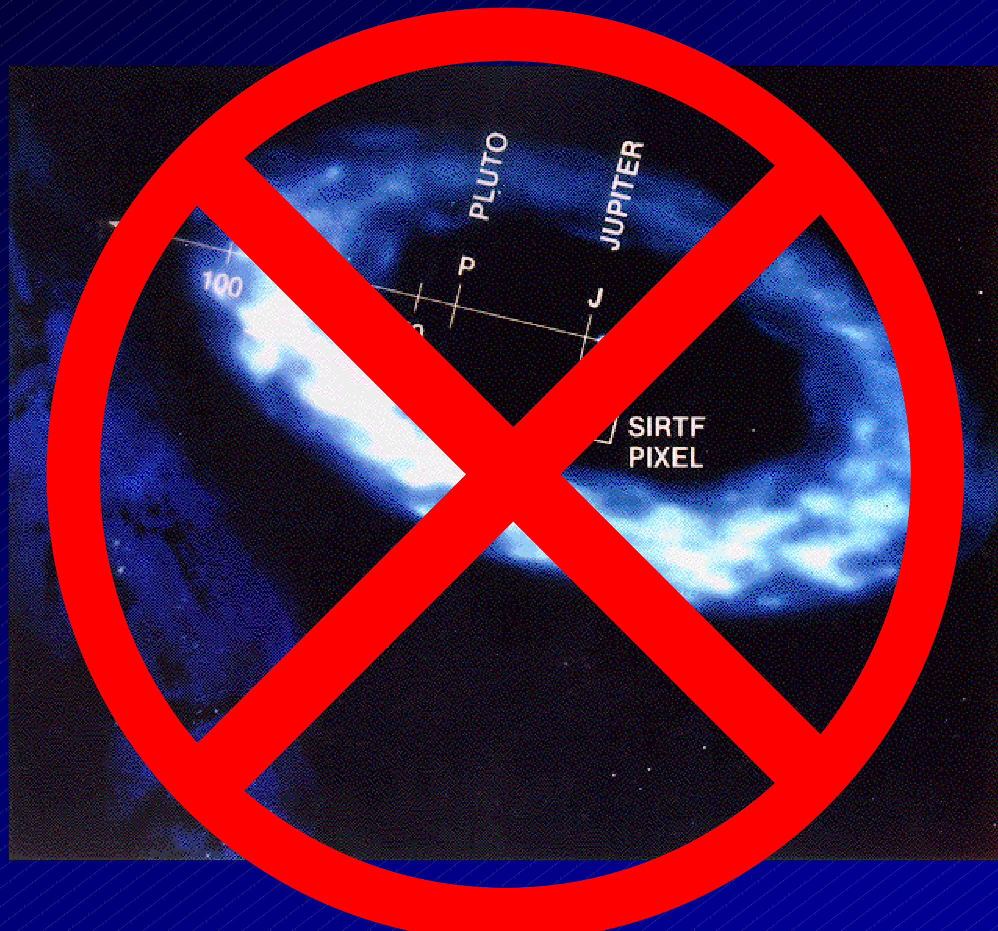


Above: Disk model & Plateau de Bure 1300 µm map by Wilner et al. (2002)

Conclusions of early *Spitzer* Disk Imaging

- **Outer extent of 24 μm emission is larger than naïve expectation in Vega, Fomalhaut, β Pictoris**
- **Disk inner holes appear to be filled in at mid-infrared wavelengths (Fomalhaut, ε Eridani, Vega)**
  - *Dust spiraling in from outer disk ?*
  - *Or do inner asteroid belts provide a 2nd dust source region ?*
  - *Shows unique value of mid-IR to probe inner disk region*
- **Strong disk asymmetry seen only in Fomalhaut; submillimeter continuum substructures not confirmed in Vega and ε Eridani**
  - *Vega is a real mystery !!*

Why we build observatories: Pre-launch notional version of Spitzer Vega image



Herschel & SAFIR work

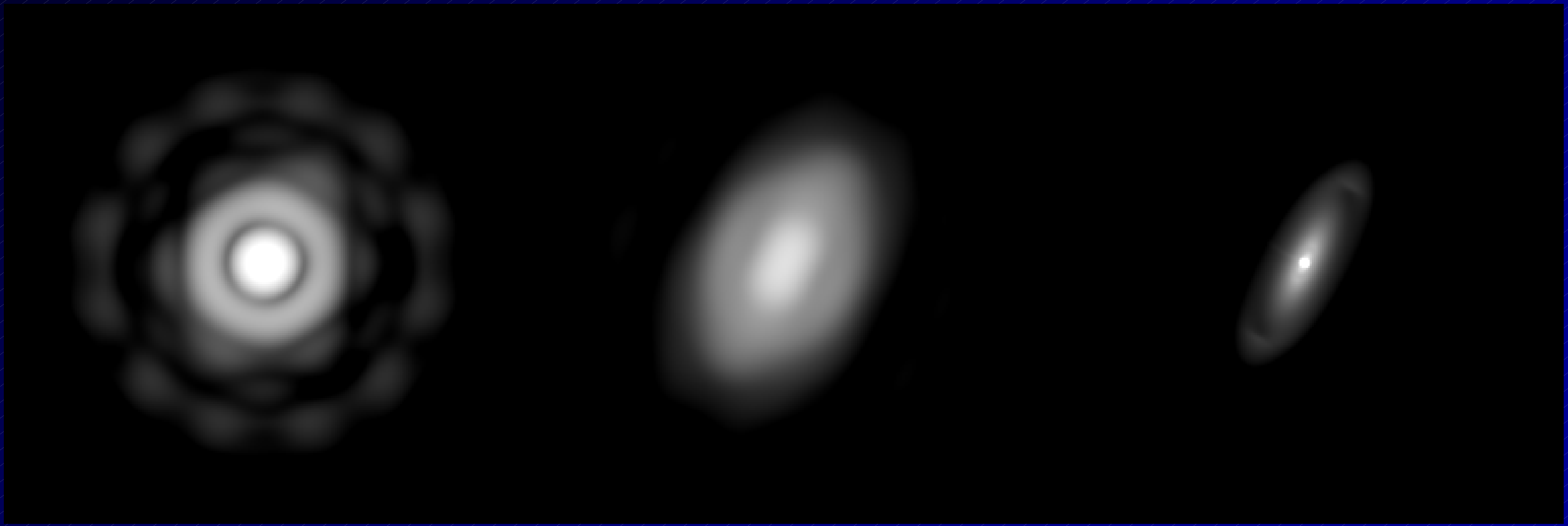
- **H_2 will be accessible to SAFIR at 28 μm, could be much more sensitive than JWST (2.25 times greater collecting area, telescope background would be hugely reduced by the lower operating temperature.**
  - *Measure disk H_2 abundance vs. disk age, spatial structure*
- **Other disk gas tracers to try with Herschel / SAFIR (do in YSO disks first, then debris disks):**
  - *[O I] 63 μm*
  - *[C II] 158 μm*
  - *Others*
- **Continuum survey with SAFIR for small dust excesses**
  - *At ~100 μm, will bemore sensitive to small amounts of dust than ALMA*
- **Resolved maps of bright, nearby disks with both facilities**

Fomalhaut disk model: Spitzer vs. SAFIR at 24 μm

Spitzer

Spitzer PSF-subtracted

SAFIR



BACKUP

Fomalhaut MIPS 160 microns

- Spectral leak seriously confuses 160 disk image
- Kate Su has done a reasonable subtraction
- Deconvolutions (Hires, MEM) of leak-subtracted image shows same double-lobe structure as 70, 850 um